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Computational Challenges of the Aerodynamic Design Process in Formula 1

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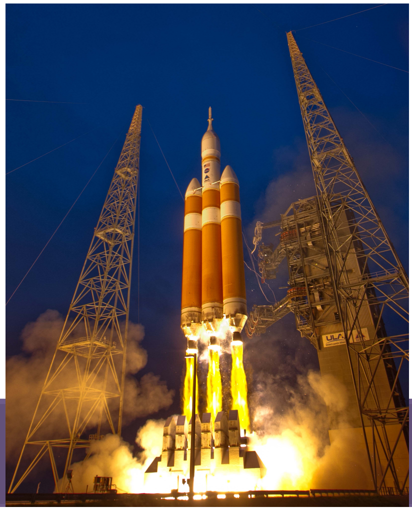
Overview

- Each sector, company or individual uses modeling and simulation tools in different ways, but the end goal is often the same.
- A ***faster***, ***quieter***, ***cheaper*** and **more *efficient*** plane, car, boat, rocket, bike or machine.
- The use of modeling and simulation tools can make these objectives possible, often in ways that wouldn't have been so easily achieved in the past.



Overview

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- Whilst these tools are used for pure scientific research, many of us here develop methods and tools that are aimed to be used as an engineering tool.
- The use of modeling and simulation in Formula 1 is not so well known, yet it shares many of the same challenges that NASA faces.
- <u>Interesting to look at how F1 achieves its engineering goals.</u>

Formula 1 – Brief Overview

- Formula 1 is one of the most popular motorsport series, as of 2015 there are 10 teams racing at 20 'Grand Prix' over the course of a year in a single-seater car, which are dictated by the rules of the Fédération Internationale de l'Automobile (FIA):
- Teams participate to typically transfer technology to their road cars (**Ferrari**, **Mercedes**, **Renault**), or for marketing reasons to boost their brand (**Red Bull**) or typically a mixture of both of these things.
- Team budgets are in the **£100-400 million** range but difficult to quantity these costs when the team also has an automotive division.

- Weight: 700kg
- Forces up to **5g** in braking and cornering
- Max Speed : 220mph
- Engine: 1.6L V6 Turbo with additional electric power : 750HP
- Acceleration (approx) **:**
  0-60mph = 2s
  0-120mph = 4s
  0-200mph = 9s

- **How does it compare to other sports (viewing figures)?**
  - Olympics : 7 Billion viewers
  - NFL: 1.8 Billion viewers
  - **F1: 1.7 Billion viewers**
  - FIFA World Cup: 1 Billion viewers
  - NASCAR: 0.7 Billion viewers
  - English Premier League: 0.5 Billion viewers

Formula 1 – Brief Overview (2)

- Variety of tools available to enable aerodynamic design:
  - Wind Tunnel (closed loop, rolling ground tunnel with 60% scale models at 40ms-1)
  - CFD (Medium sized cluster: 1000-4000 cores)
  - Simulator
  - On-track testing at races
- Combination of these are used to bring about continuous improvements throughout the year

Departments

- Aerodynamics (CFD, Experimental, Track Team)
- Structures
- Simulator
- R&D
- Manufacturing
- Marketing
- I.T
- Race Team

Restrictions

- Maximum 30TFlops of CFD use per reporting period (8 weeks)
- Maximum 30 hours of Wind Tunnel 'Wind-on' Time
- Maximum 80 WT runs per week
- Maximum 60hrs Tunnel Occupancy each week
- WT=WT_max (1-CFD/CFD_max) i.e 50/50 means 15 TFLops of CFD + 15 hrs of WT per 8 weeks

Design Process

Initial CFD Analysis

CAD (CATIA,NX) → Pre-Processing/ Clean up (e.g ANSA) → Mesh+Solve+Post (Fluent, Star-CCM+, OpenFoam)

5hrs per run (1-2 week total)

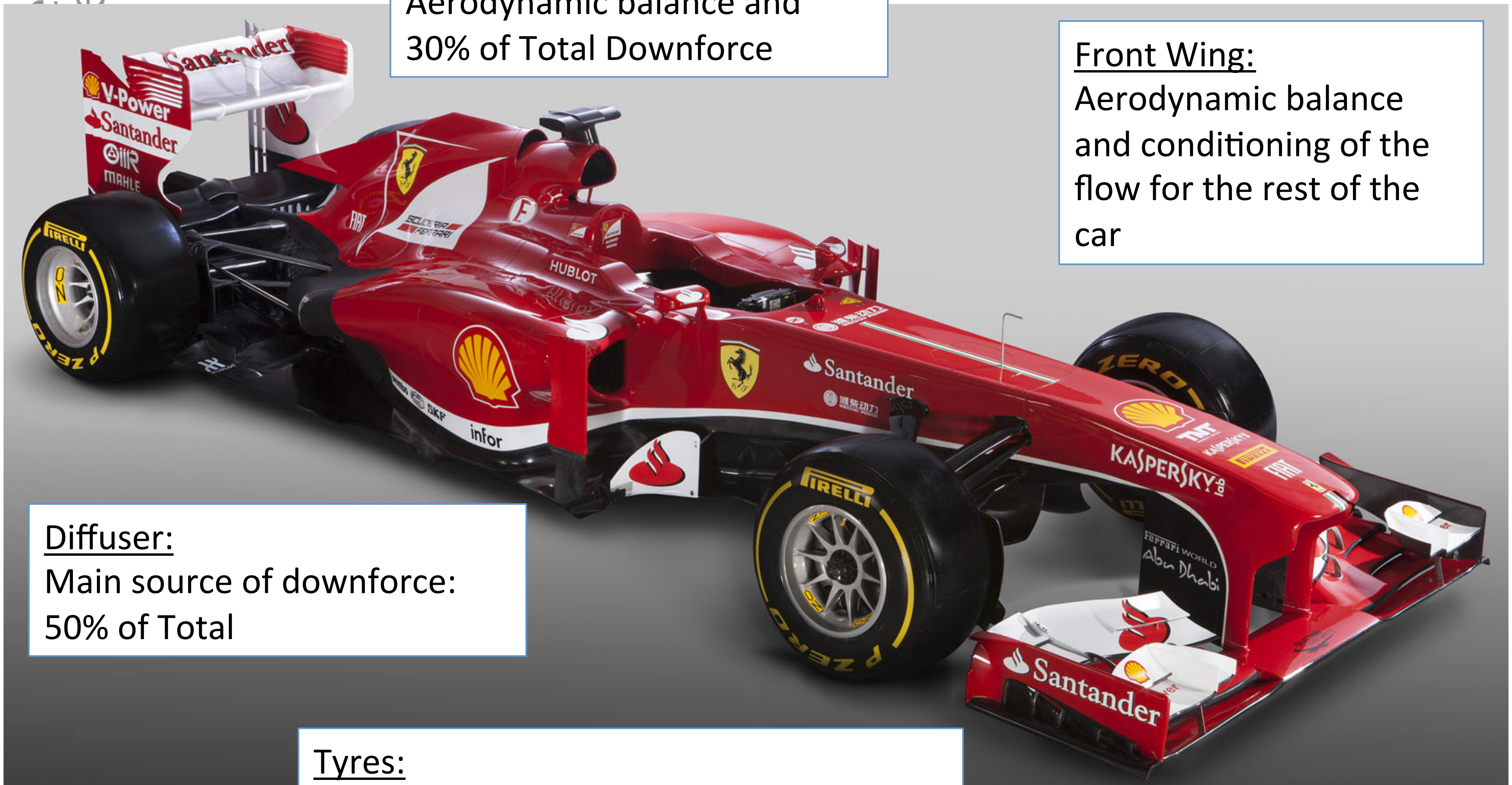
60% size 3D Laser Printer model for Wind Tunnel Test → Wind Tunnel Test Programme → Good -> ***Track Test*** / Bad - > ***Back to CFD***

1-2 week from CFD

Full-size CAD work + structural analysis → Practice Session at Race Track → Good -> ***Race day*** / Bad - > ***Back to CFD***

1-2 weeks from WT Test

Total: 3-6 weeks from Initial CAD to racing at Grand Prix



Multi-Element Rear Wing:
Aerodynamic balance and 30% of Total Downforce

Front Wing:
Aerodynamic balance and conditioning of the flow for the rest of the car

Diffuser:
Main source of downforce: 50% of Total

Tyres:
Major challenge for CFD modelling and very influenical on the car flow physics

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Accessing performance

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- The design cycle has been described but how does a team assess whether a new design offers a laptime improvement?
- A new part on the car has to make the car quicker over the **whole** track over a wide range of flow conditions:
  - *Yaw, Steer, Roll, Front Ride Height, Rear Ride Height*
- Teams use a ‘map’ system to try to reduce this problem into a single value that designers can use to assess whether their design will offer a laptime improvement

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Generating a Wind Tunnel Map

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Selection of representative tracks

Measure Yaw, Steer, Roll, Front Ride Height, Rear Ride Height, Cx (forces) at each point on the track for each circuit

Use/build a simulator programme to model a car on each track

In the simulator, at each point on each track increase/ decrease Cl and assess the effect this has on the laptime

Build a 5-dimensional space of laptime delta vs. Yaw, Steer, Roll etc

Analyse all this data to highlight the most important points to consider for testing

Select 20 most highly weighted conditions (i.e Yaw, Steer, Roll etc) and run each WT programme for these points

Multiple the resulting Clf,Clr by its own weighting factor and then average oover the 20 runs to get a single number

If a new design provides greater than this number then it will provide a laptime improvement

Many different ways of assigning weighting but this highlights the general approach

The use of CFD

The role of CFD

- Too expensive (time and money) to test each design in the WT.
- CFD offers a rapid design tool to assess conceptual ideas as well as exploring design space (up, down,left,right etc)
- Decisions has to be made on what points on the WT map to run, not possible to run all due to restrictions.

What can a designer get from CFD?

- Visualize vortices and control them
- Skin friction to check stall
- Pressure distribution to optimize airfoil
- Forces to check drag, downforce
- Optimization (Adjoint etc)

CFD Strategy

Simulation

- Designs are often judged on their trends rather than absolute figures (RANS not accurate enough).
- Cannot run each of the 20 WT map points thus highly weighted points are focused upon

Commerical vs. opensource

- Fluent/Star-CCM+ vs. OpenFoam and others is a balance between license cost and a large CFD tools group.
- The push is for more efficient, faster solvers and turbulence models.
- Each team decides on whether more runs with lower accuracy vs. less runs with higher accuracy

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Why industry still uses RANS? F1 example

RANS

- Steady RANS (typically used in industrial calculations).
- Typically mesh an entire car from CAD with 80 million cells using 8 cores in **1.5 hrs**
- Reach convergence (based upon standard deviation not changing by 1e-5 for the global forces) using **128 cores** in **3hrs**
- Post process the data (streamlines, contours, forces, pressure tappings) into an automated report in **30mins**

Hybrid RANS-LES

- Conservative estimate would need a mesh of approximately 5 billion cells created using 128 cores in **2 days using 2TB RAM**
- Assuming 0.2mm smallest cell with $40ms^{-1}$, time step = $0.0001/40=5e^{-6}$
- 25 flow-throughs required (2m car). $0.05/2.5e^{-6}$=10,000x25= **250,000** time steps.
- Assume 10s per iteration on **8192** cores (industrial scaling)=**28.5 days**
- Post process the > 2TB data per run. **0.5days? Storage??**

Total time from Design to Result:
RANS: **5hrs** (3-8% accuracy when its working well, but depends on lengthy mesh optimization and solver optimization)
Hybrid RANS-LES: 30 days (1-3% accuracy-still depend on many factors, underlying RANS model, inflow conditions, near-wall resolution!)

Back of an envelope calculations, but broadly correct

Selection of a suitable RANS model

- Formula 1 cars consist of many vortices shed from many airfoil-type surfaces
- Mild separation from the wing elements
- Massive separation from the rotating tyres
- CFD model ideally has to capture these affects
- **Must be robust, repeatable and converge in a steady RANS framework**

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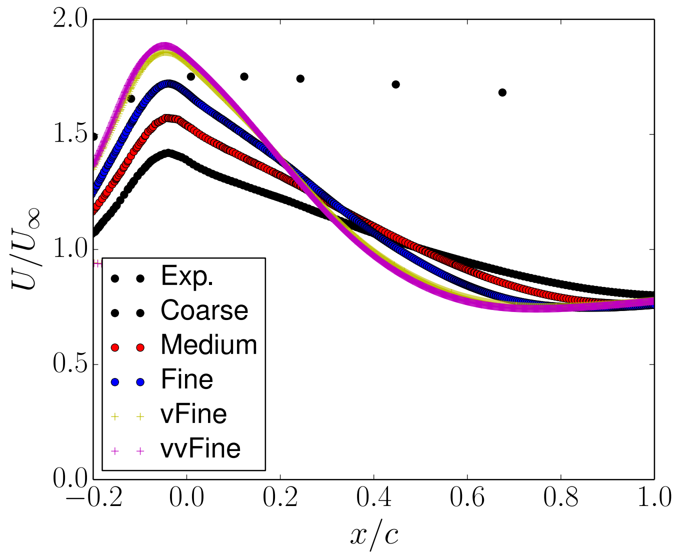
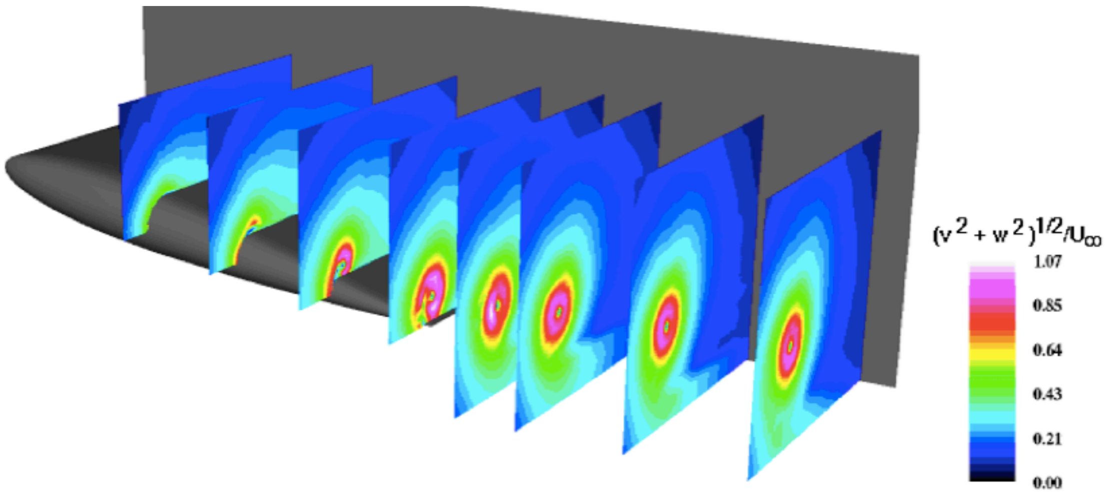
NACA0012 Wing tip

- Useful validation case to assess model capability to capture vortices
- Re=4.6 x10^6 at AOA=10
- Highlights importance of accounting for rotation and curvature.
- Requires >250 million cells for mesh convergence (Independently confirmed by myself and Dr Mike Olsen)



Mesh convergence for SST model.
vvFine=300 million cells



Experimental PIV

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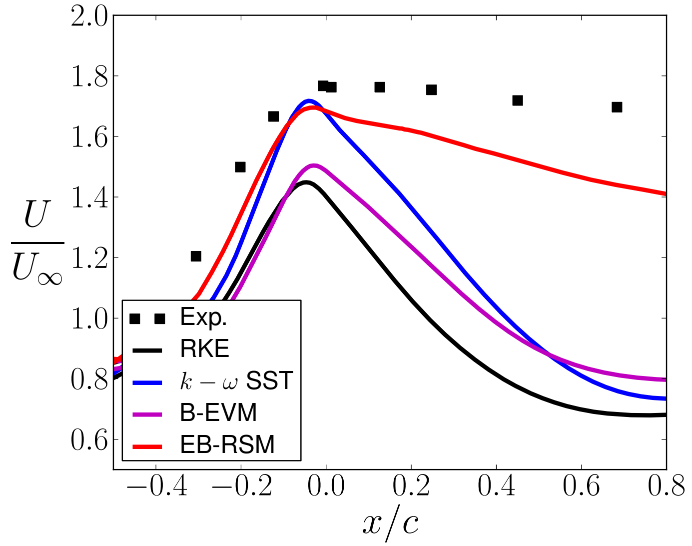
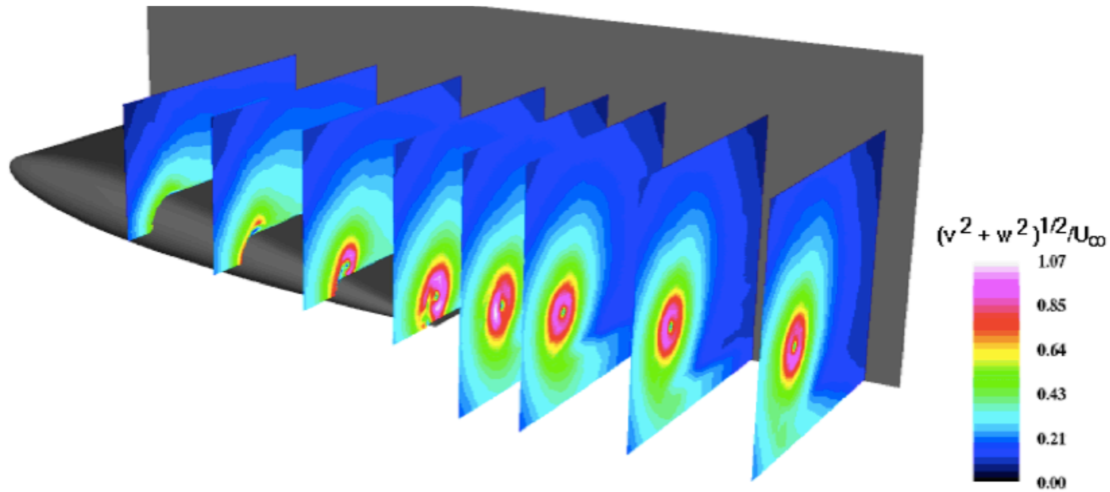


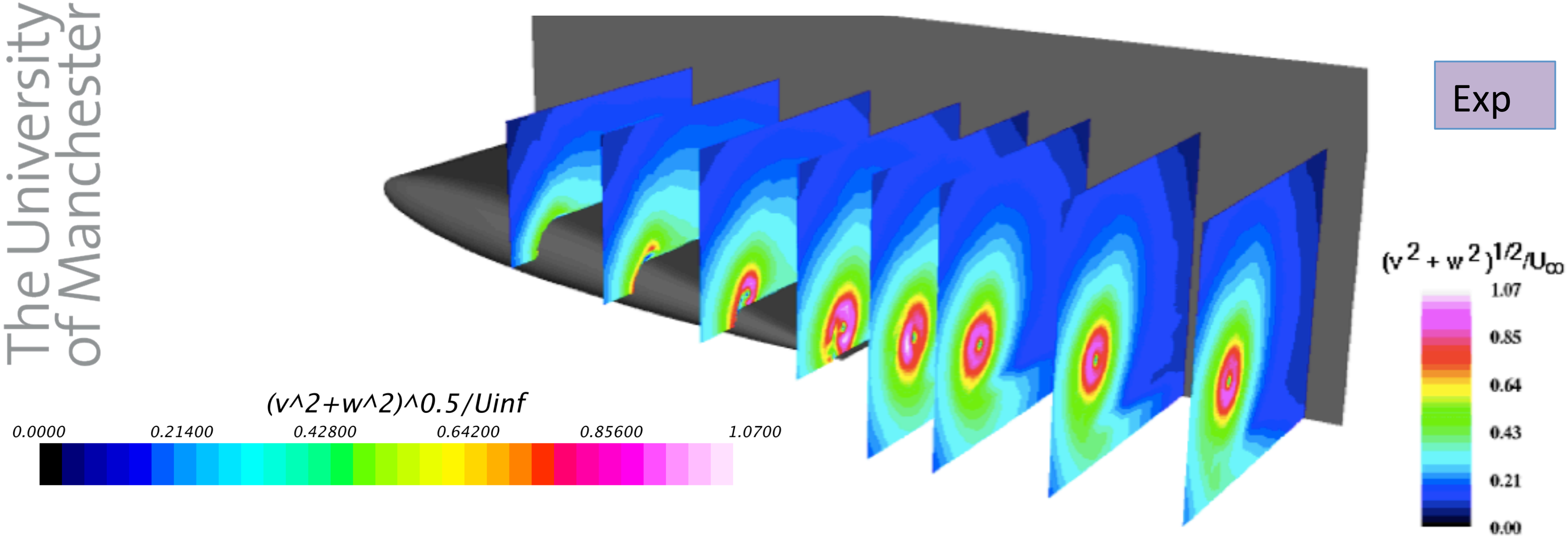
Trend observed is true regardless of mesh resolution



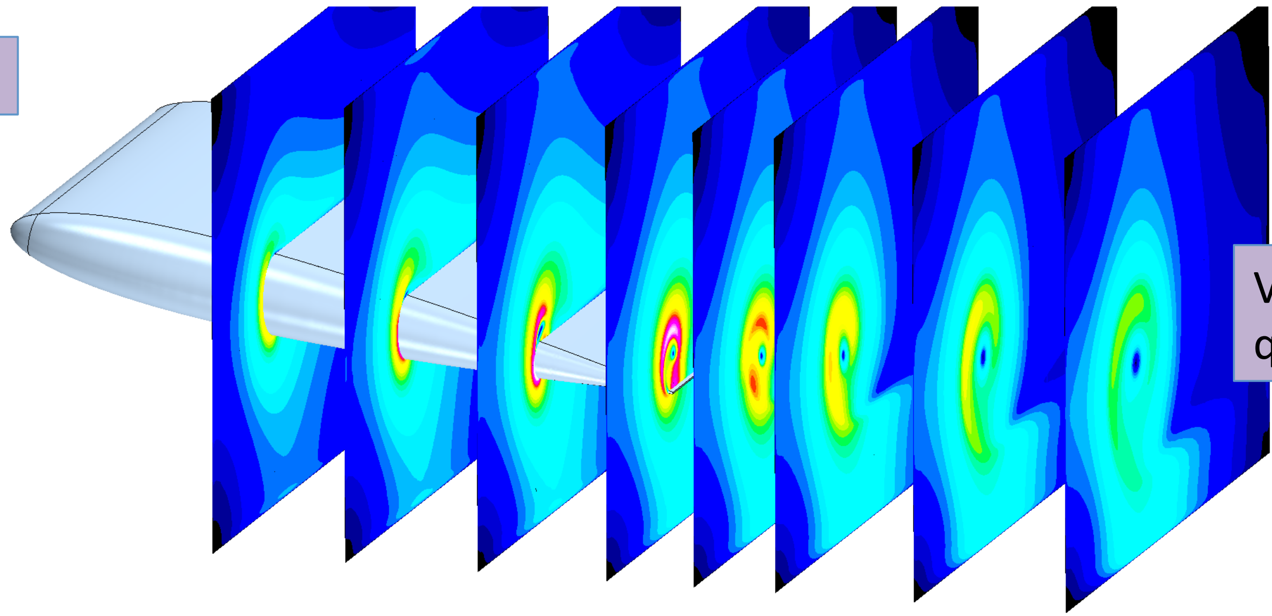
Experimental PIV

Cross flow (RKE)

Exp

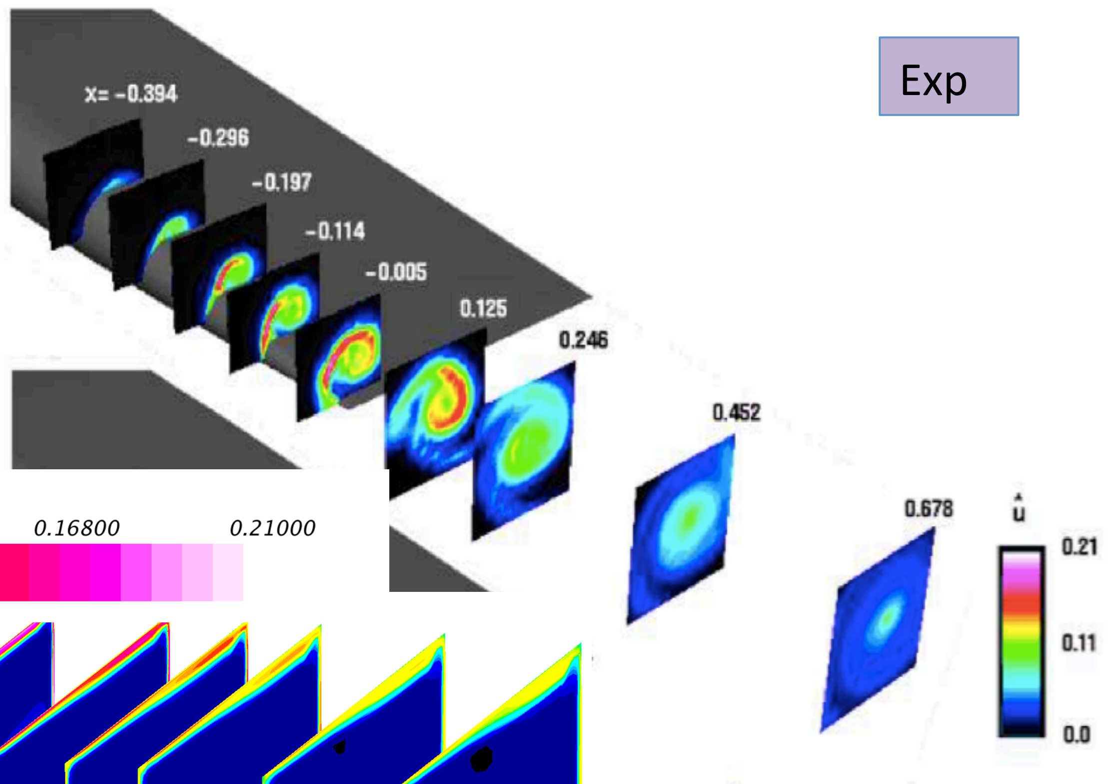


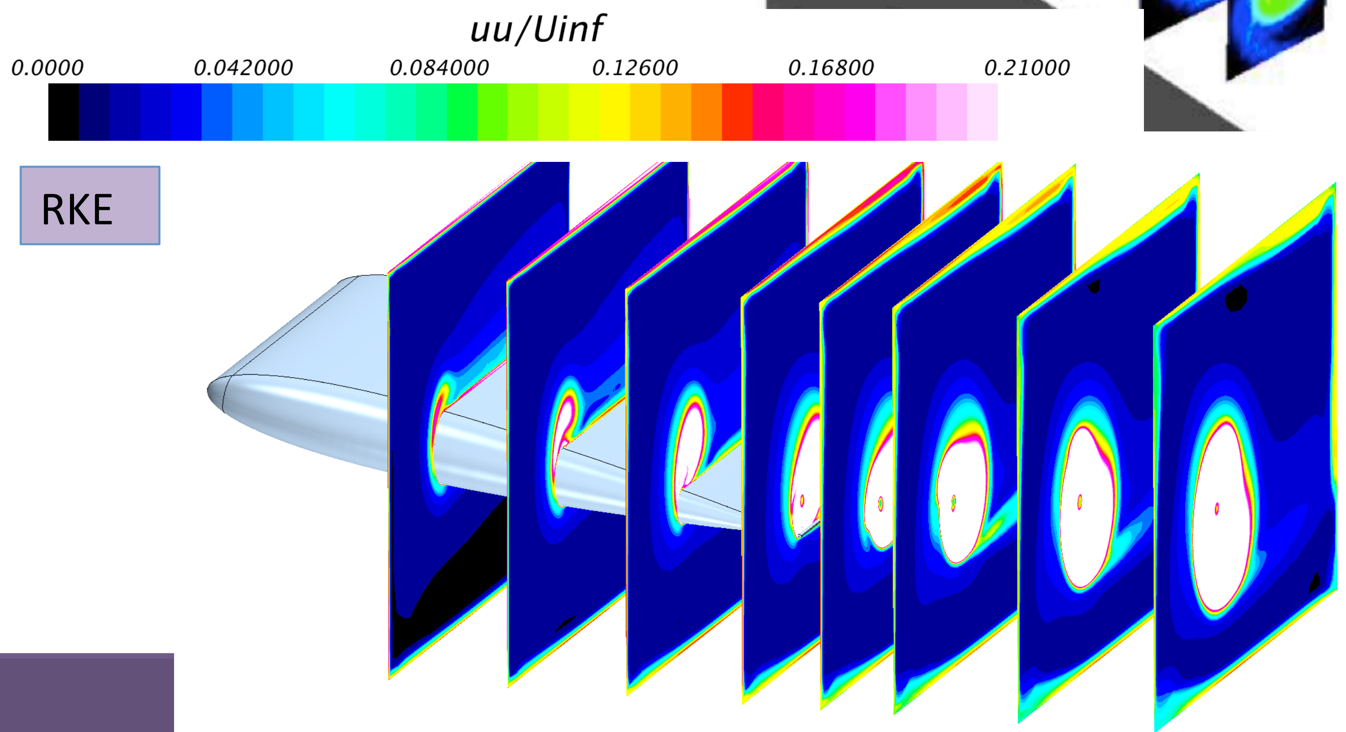
RKE



Vortex dissipated too quickly

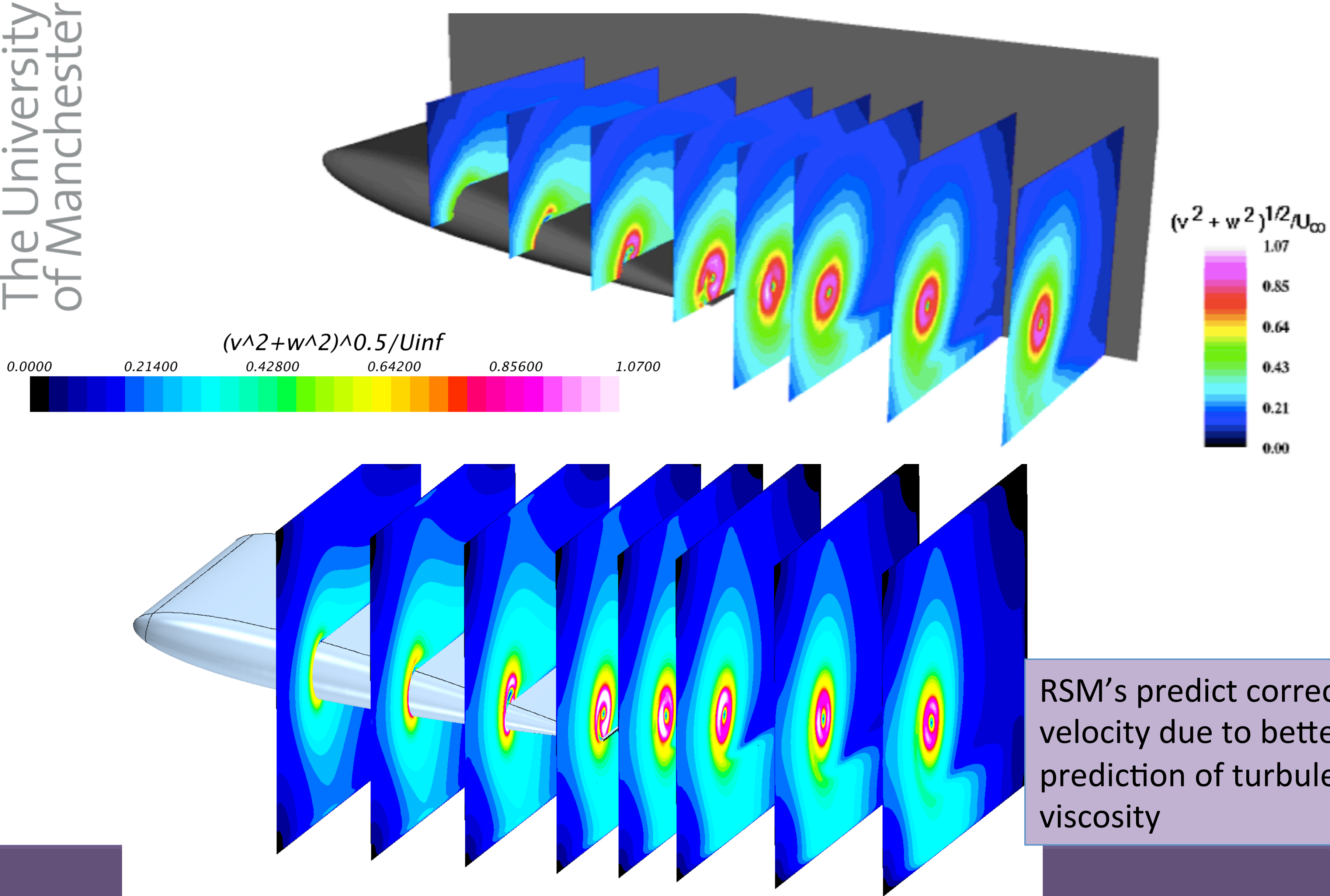
Normal stress uu (RKE)





Over-prediction of Reynolds stresses, thus damping out the vortices too quickly.

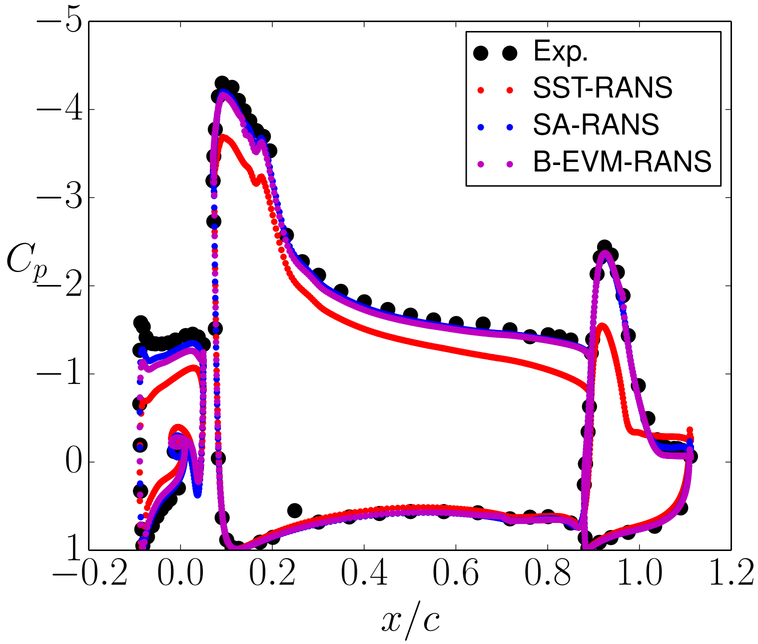
Results – Cross flow (EB-RSM)

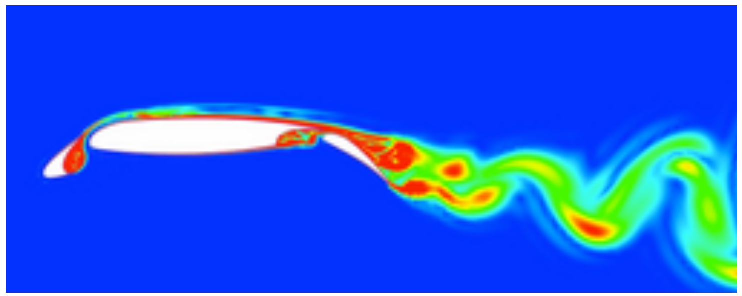


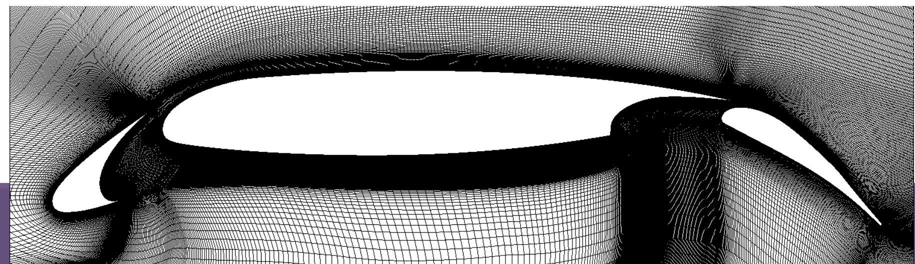
RSM's predict correct velocity due to better prediction of turbulent viscosity

3-element high-lift airfoil

- DLR F15 high-lift 3-element airfoil provides useful assessment of turbulence models for high-lift devices (i.e Rear wing of F1 car)
- Lacks the vortices due to the side walls (modelled periodic)
- $Re=2.09 \times 10^6$
- SA model does well, but SST over-predicts separation. Other models largely agree with experimental values (for Cp). For spectra/ acoustics RANS often not suitable.

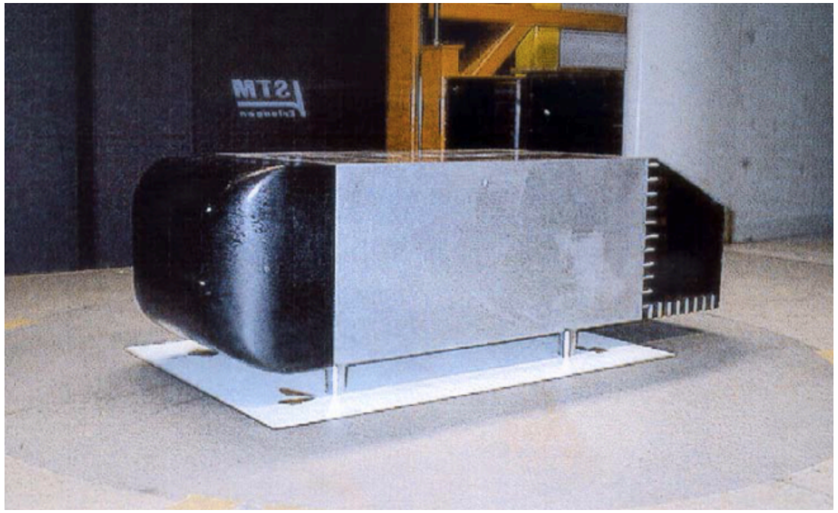


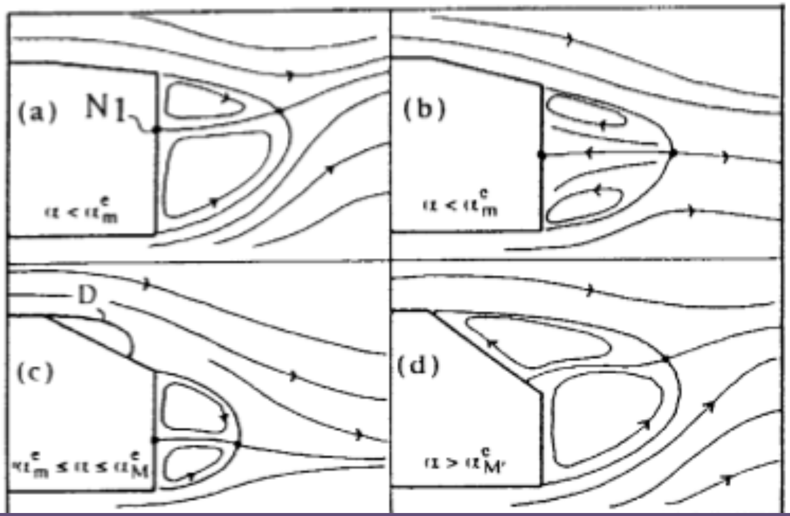




Ahmed car body

- Original experiment by Ahmed et al. [1] and later Lienhart et al. [2] (and others)
- Re= **7.68 x 10^5** (based upon body height H and free-stream velocity U)
- A range of slanted back angles were investigated to match possible car rears e.g fastback, estate.
- Combination of separation and vortices

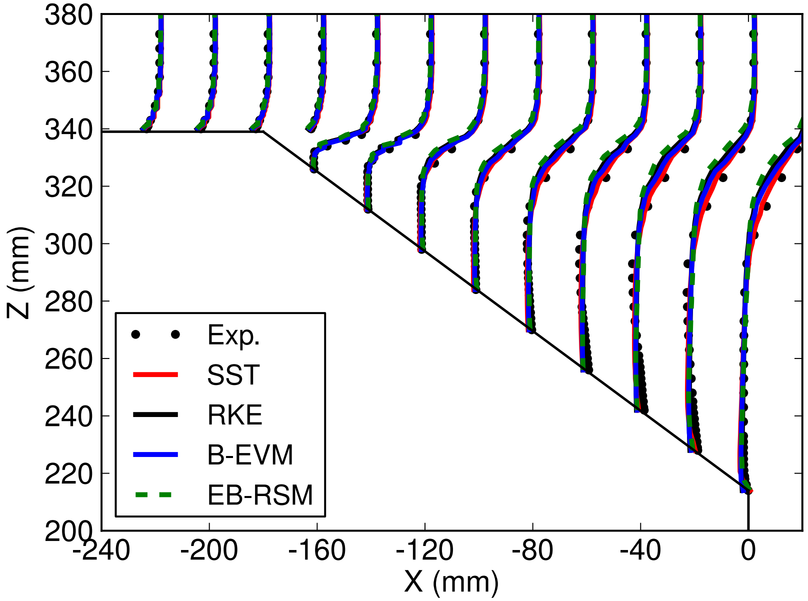


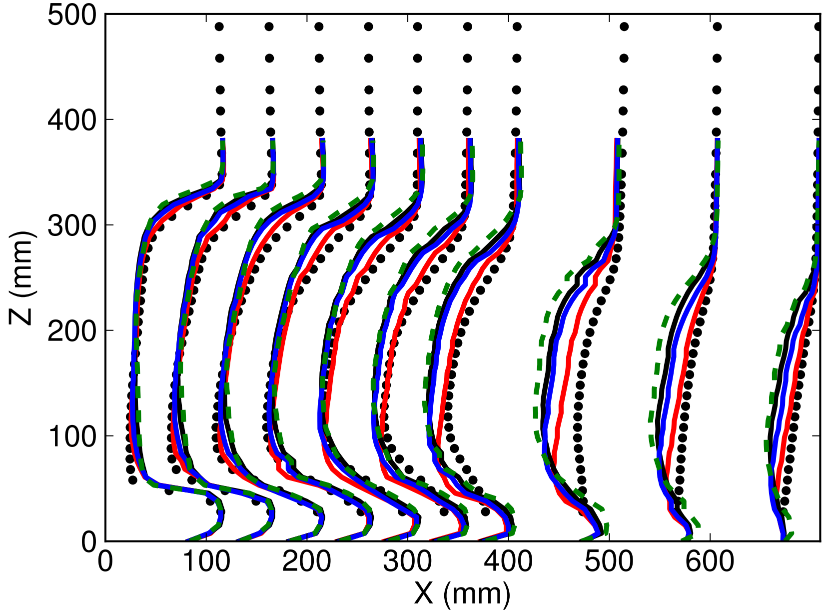


[1] Ahmed, S. R., Ramm, G., & Faltin, G. (1984). Some salient features of the time averaged ground vehicle wake. SAE-Paper 840300.
[2] Lienhart, H., & Becker, S. (2003). Flow and turbulent structure in the wake of a simplified car model. SAE, 01(1), 0656.

Ahmed Car body (35 degrees)

- Most RANS models perform well for this configuration Little difference between the models (except much further downstream of the body). SST slightly better than the other models in the rear recirculation region.
- Correctly capture levels of TKE in the initial separated shear layer





Streamwise velocity on the symmetry plane

Ahmed Car body (35 degrees)

- Most RANS models perform well for this configuration (unlike 25 degrees)
- Little difference between the models (except much further downstream of the body). SST slightly better than the other models in the rear recirculation region.

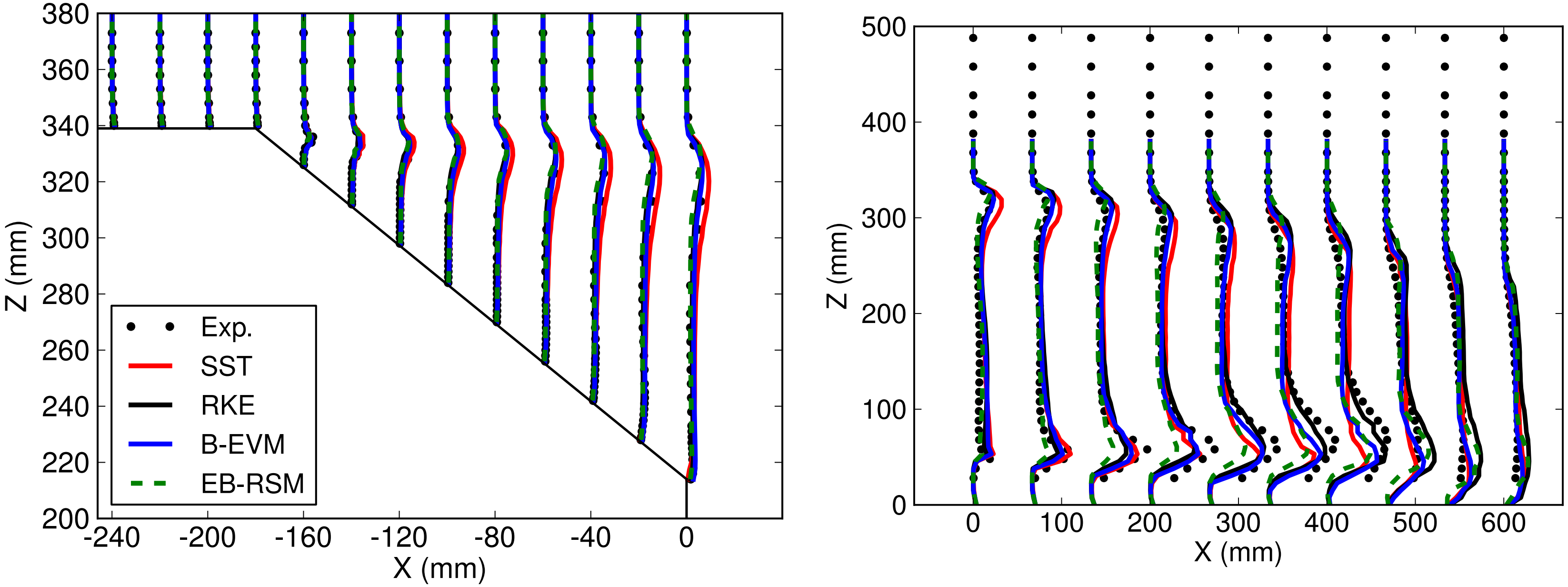
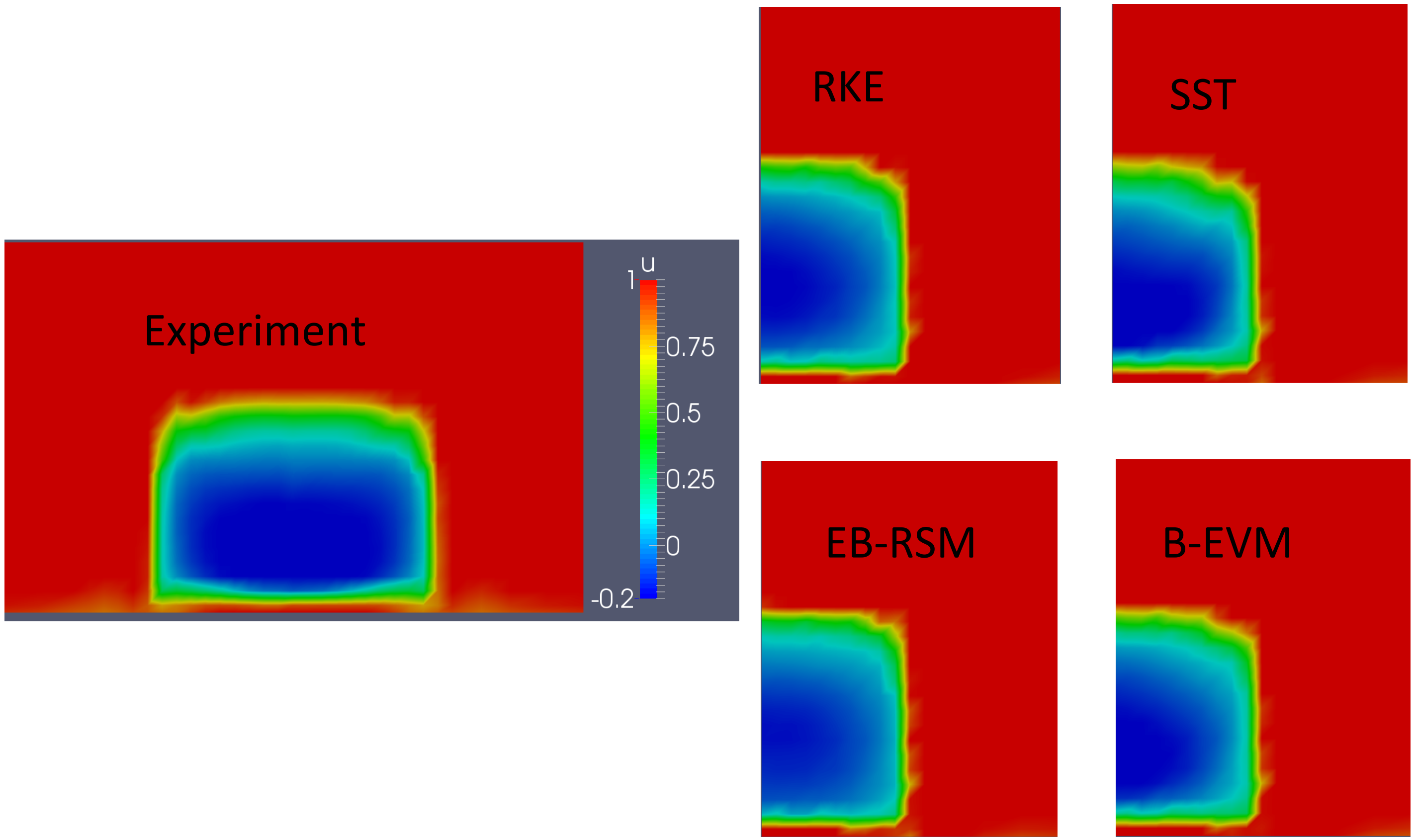


Figure 1: Turbulent Kinetic Energy (TKE) on the symmetry plane

Ahmed Car body (35 degrees)

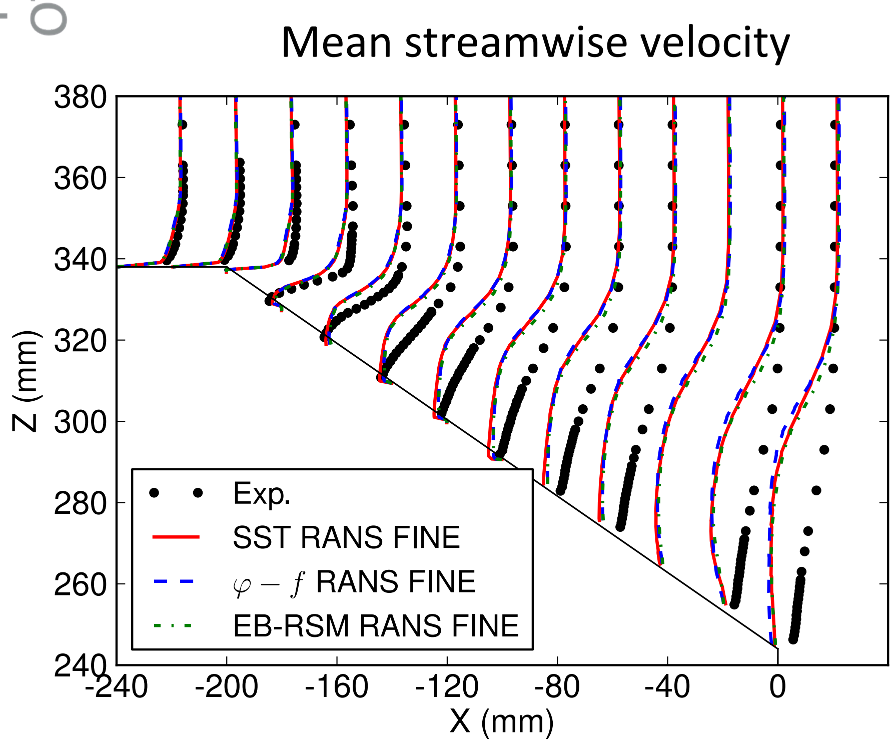
- All models capture the main features of the flow.
- For engineering purposes all the models provide a good representation of the flow

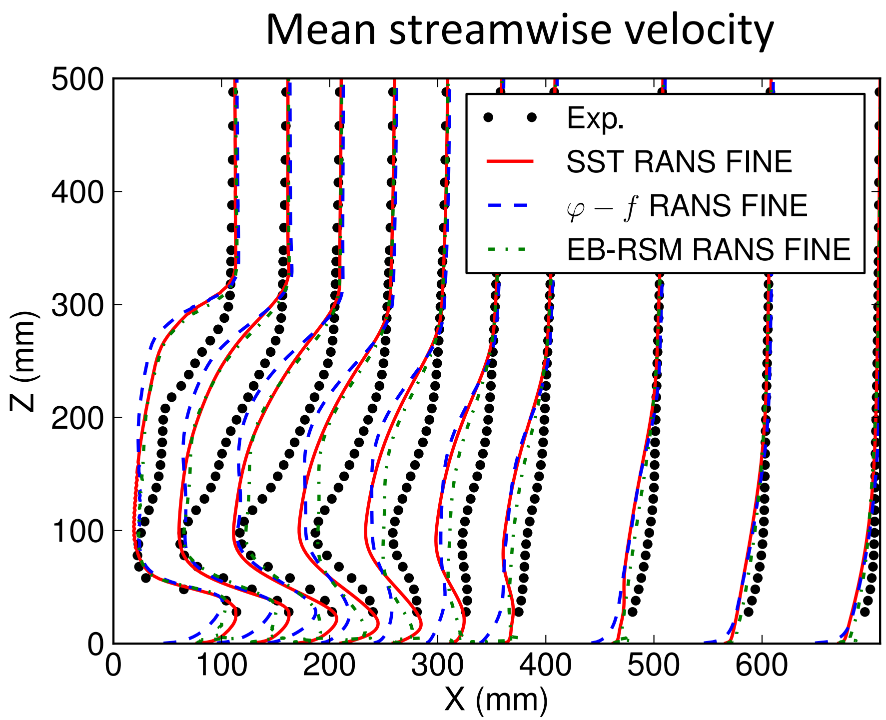


Streamwise velocity 80mm downstream of the back of the Ahmed body

RANS results - Velocity

- At 25 degrees no URANS model (whether EVM/RSM, or ε/ω) can correctly prediction the velocity field. All models under-predict the level of turbulence in the initial separated shear layer and as a result over-prediction the separation region.





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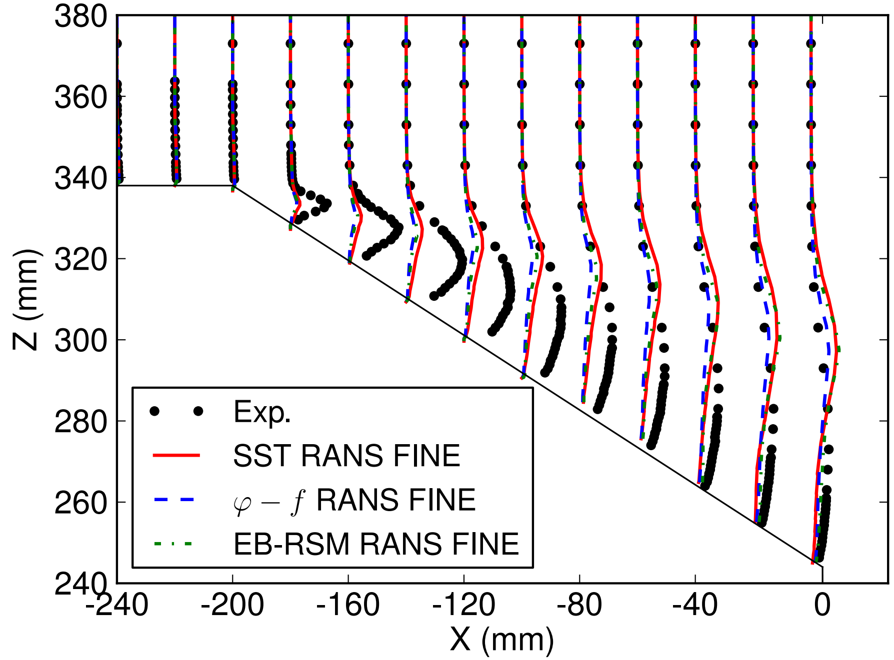
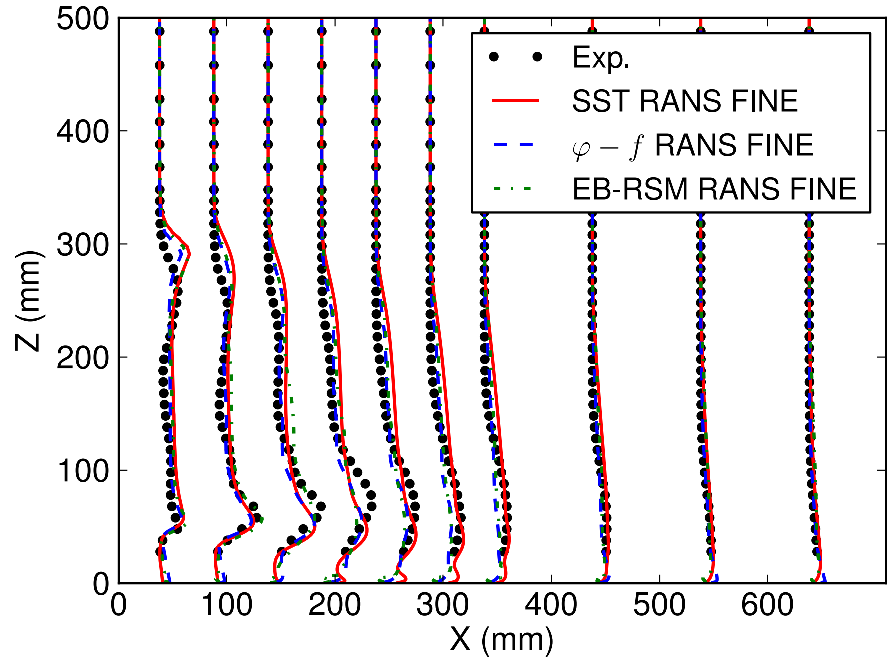
Mean TKE



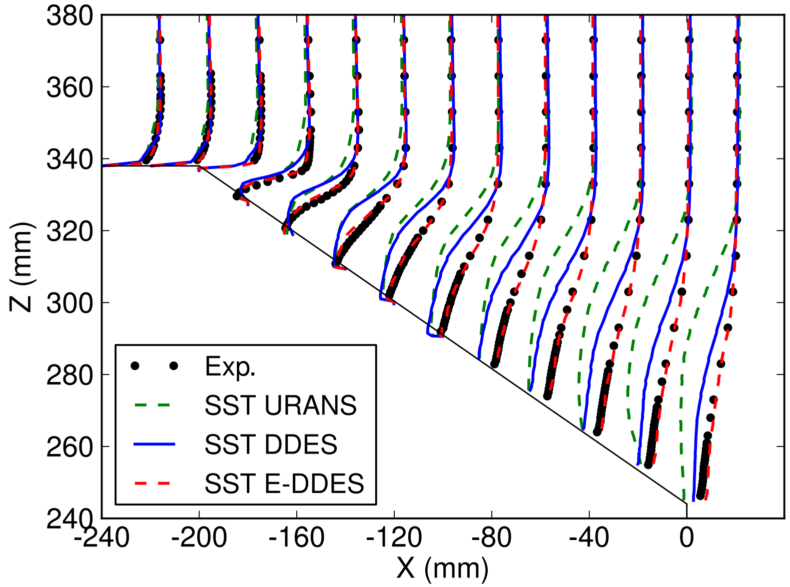
Mean TKE



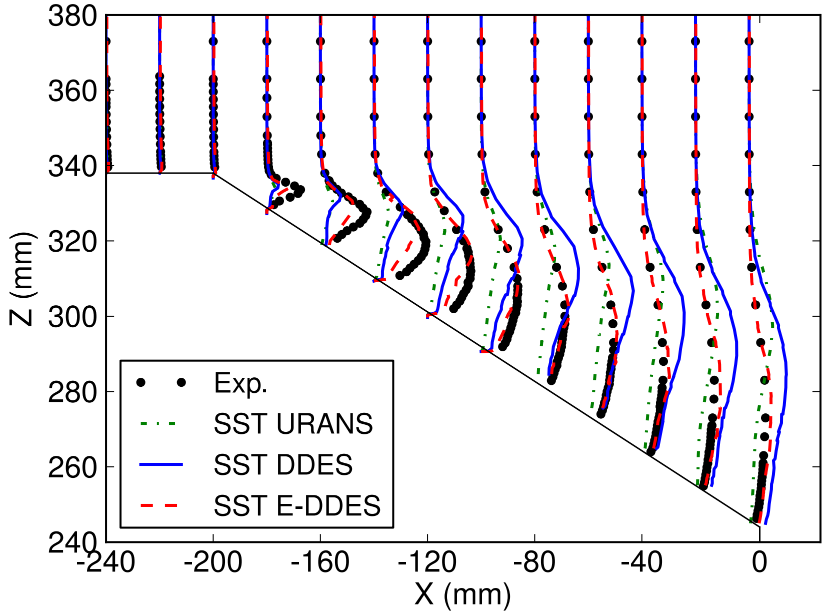
DDES

- Much better agreement with hybrid RANS-LES but the cost compared to steady RANS is much greater.
- Current state of the art RANS models cannot capture this flow. New models to capture the flow physics in the initial separate shear layer are needed.

Mean Velocity

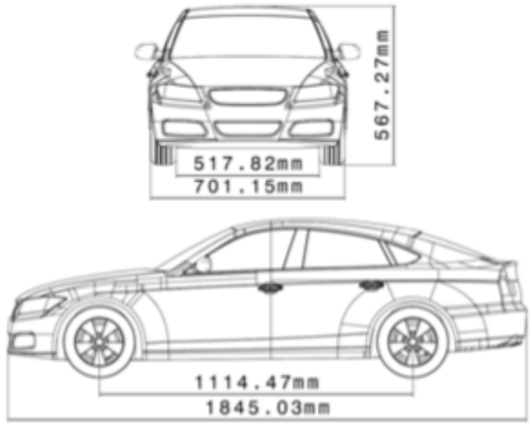


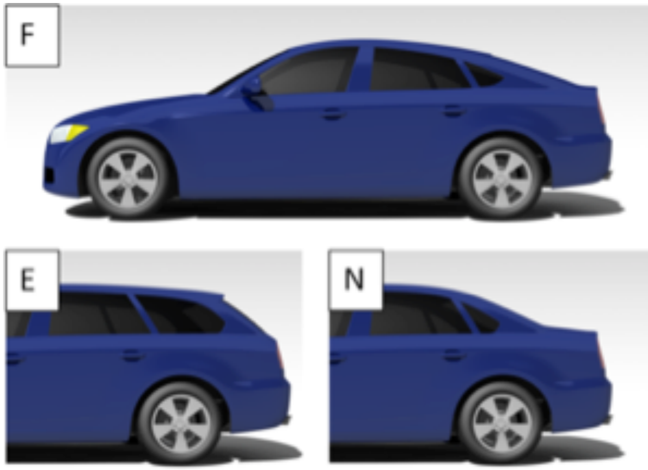
Mean TKE



DrivAer automotive model

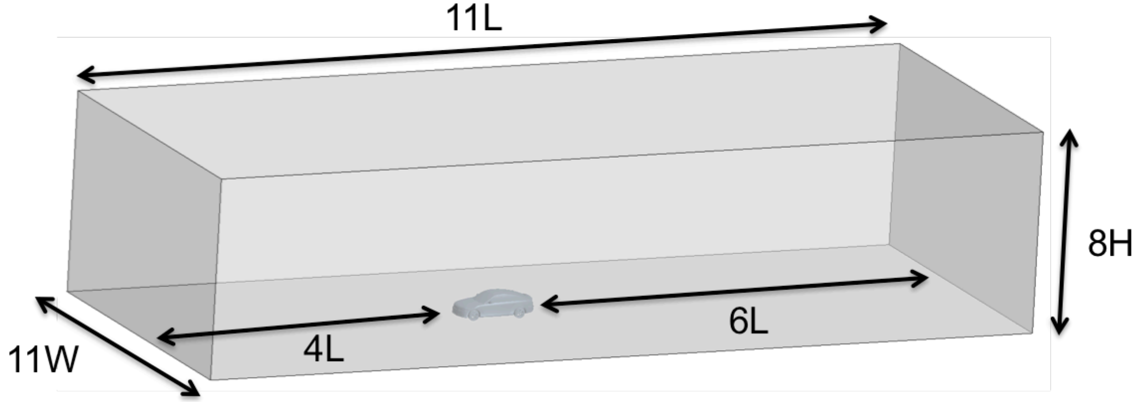
- This is joint project between BMW, Audi AG and the Institute of Aerodynamics and Fluid Mechanics of the Technische Universitat Munchen (TUM)
- Three car configurations: estate, fastback and notchback.
- Several variants were also investigated (wheel on/off, smooth/detailed underbody, mirrors on/off)

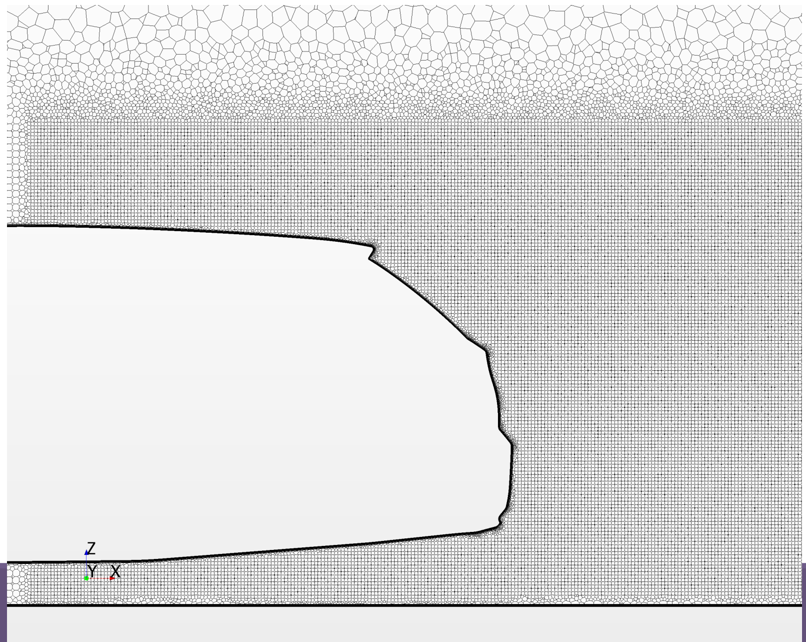




Solver setup and Mesh

- ***Re=4.87x10^6* based upon car Length, *L=1.85m***
- Low y^+ polyhedral mesh (80 million) with 25 prism layers within the boundary layer.
- **SA, Realizable K-ε, SST, B-EVM, EB-RSM**
- Star-CCM+ Coupled Solver (2nd order upwind for momentum & turbulent quantities), Algebraic Multigrid method + Grid sequencing to initialize the flow-field.
- Inlet/outlet conditions + no-slip for Ahmed car body, slip conditions on WT walls. 1% turbulent intensity, 20 turbulent viscosity ratio
- Ran until the standard deviation of the drag coefficient < 1x10^{-5} over 500 samples + residuals of momentum and turbulence below 1x10^{-5}





Results – Slices

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	Estate	Fastback	Avg. Error
Exp.	0.296	0.254	
SA	0.280 (**-5.4%**)	0.260 (**+2.3%**)	**4.3%**
RKE	0.260 (**-9.8%**)	0.244 (**-3.9%**)	**8.0%**
SST	0.275 (**-7.1%**)	0.260 (**+2.3%**)	**4.7%**
B-EVM	0.253 (**-14.5%**)	0.2435 (**-4.1%**)	**5.2%**
EB-RSM	0.256 (**-14.5%**)	0.2482 (**-2.3%**)	**8.4%**
Hybrid RANS-LES	0.306 (+**3.0%**)	0.259 (+**1.6%**)	**2.3%**

- **No single RANS model can predict all cases correctly.**
- Ones which predict the best for one configuration, are then the worse for another.
- Delta from one car to another has more than **50% error.**
- **RSM** is the worse performing**,** with **SA** the best
- Hybrid RANS-LES (SST-IDDES) gives lower error with much better prediction of geometry delta

	Delta (pts)	Error
Exp	-42	
SA	-20	52.3%
RKE	-16	61.9%
SST	-15	64.2%
BEVM	-10	76.2%
EBRSM	-8	80.9%
Hybrid	-46	+9%

HPC considerations

- High Performance Computing (HPC) is a key enabler for the future increased use LES and hybrid RANS-LES, even though F1 is currently restricted by Regulations.
- Reality is that most industrial users still use commerical or in-built codes which can't reach the level of scalability of highly tuned codes.
- Industry takes a hard-nosed view of only moving to more advanced methods if the increase in accuracy does not damage their workflow, thus **24/48hrs** turn-around times.
- Efficiency is key, running 50 iterations of a design with RANS (which has 10% error but captures trends), is often seen as more important than a single LES or hybrid RANS-LES that gives you a 3% error, but only gives you a single design point.

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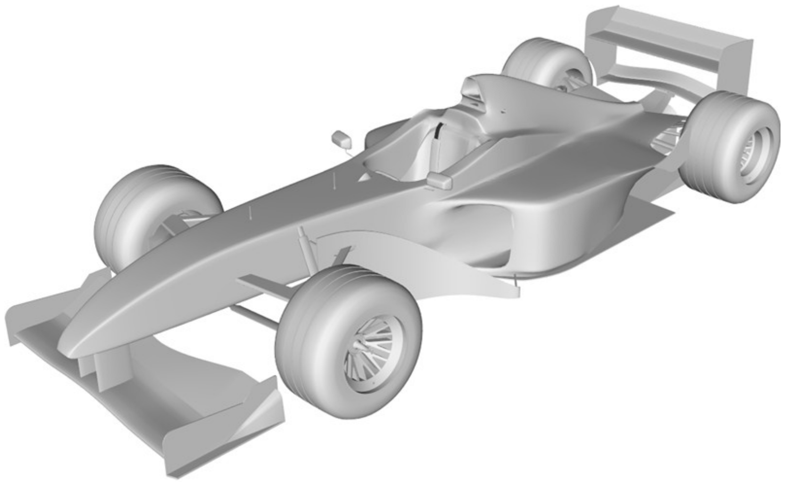
Formula 1 car

F1 Example

- A formula 1 car combines most of the flow features from the previous test cases into one single geometry. In theory a turbulence model should capture all of these flow physics to be able to correctly predict the flow.
- In practical terms, error cancellation plays a large role, and limited experimental data makes turbulence model development challenging



Simulated model is a real F1 car but image here is just taken from the internet

Formula 1 car

- Mesh
  - Half-car 90 million cells (mixture of high and low y+ resolution)
- Boundary conditions
  - Rotating Tyres, moving ground, inlet/outlet, slip walls
- Numerical scheme
  - Incompressible Coupled Solver, 2^{nd} order upwind for convective terms
- Turbulence Model
  - SA, SA-RC, SST, v2f, RKE, EB-RSM

Forces

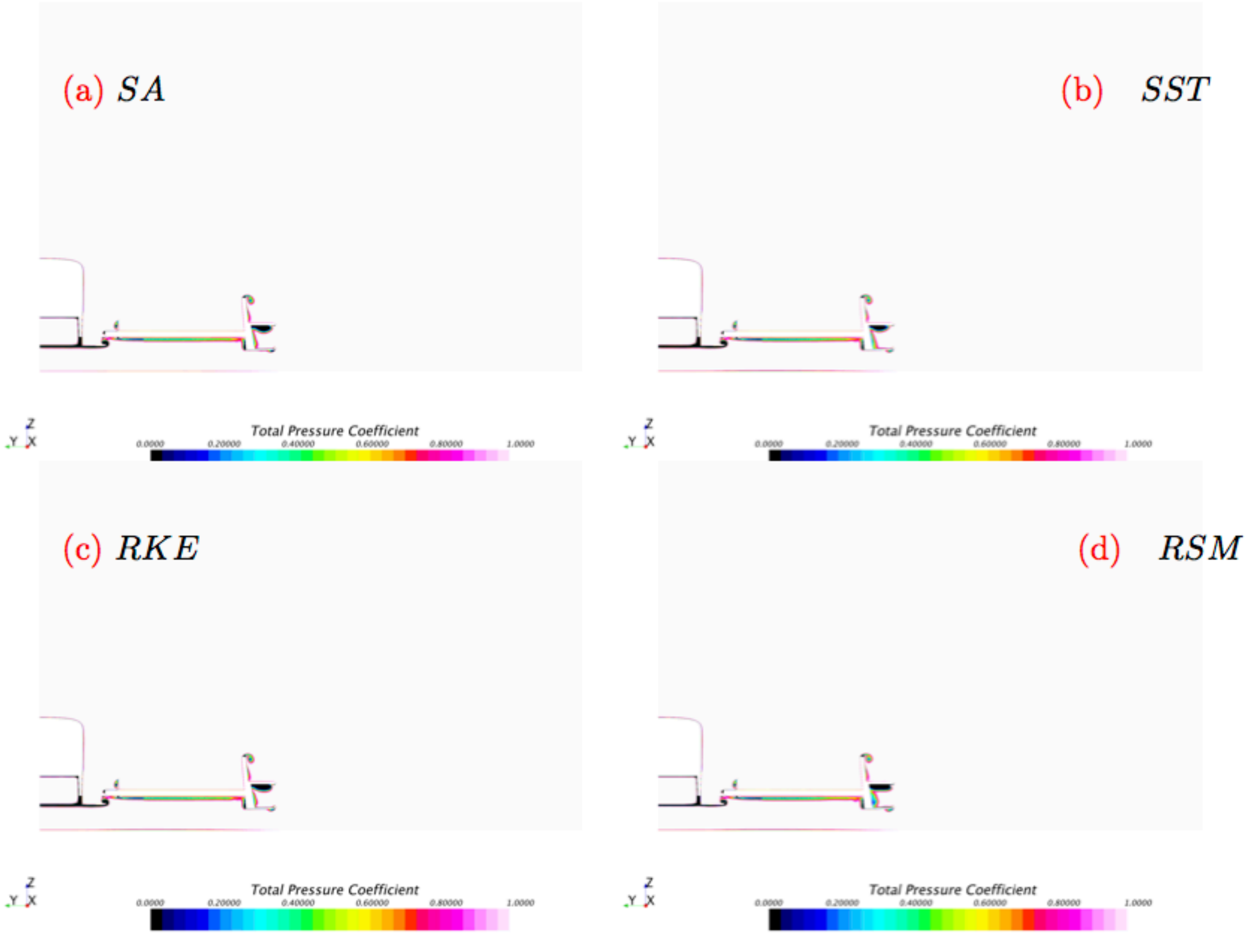
Model	CL	Cd
SA	***Baseline***	***Baseline***
SA-RC	***+2.0%***	***-1.1%***
RKE	***0.5%***	***0.95%***
v2f	***0.25%***	***2.5%***
SST	***-2.6%***	***3.0%***
EB-RSM	***1.5%***	***-2.6%***

- All models under predict by more than 10% from experimental values.
- Numbers are scaled by the value predicted by the SA model.
- **No delta computed but these show the greatest differences between models**

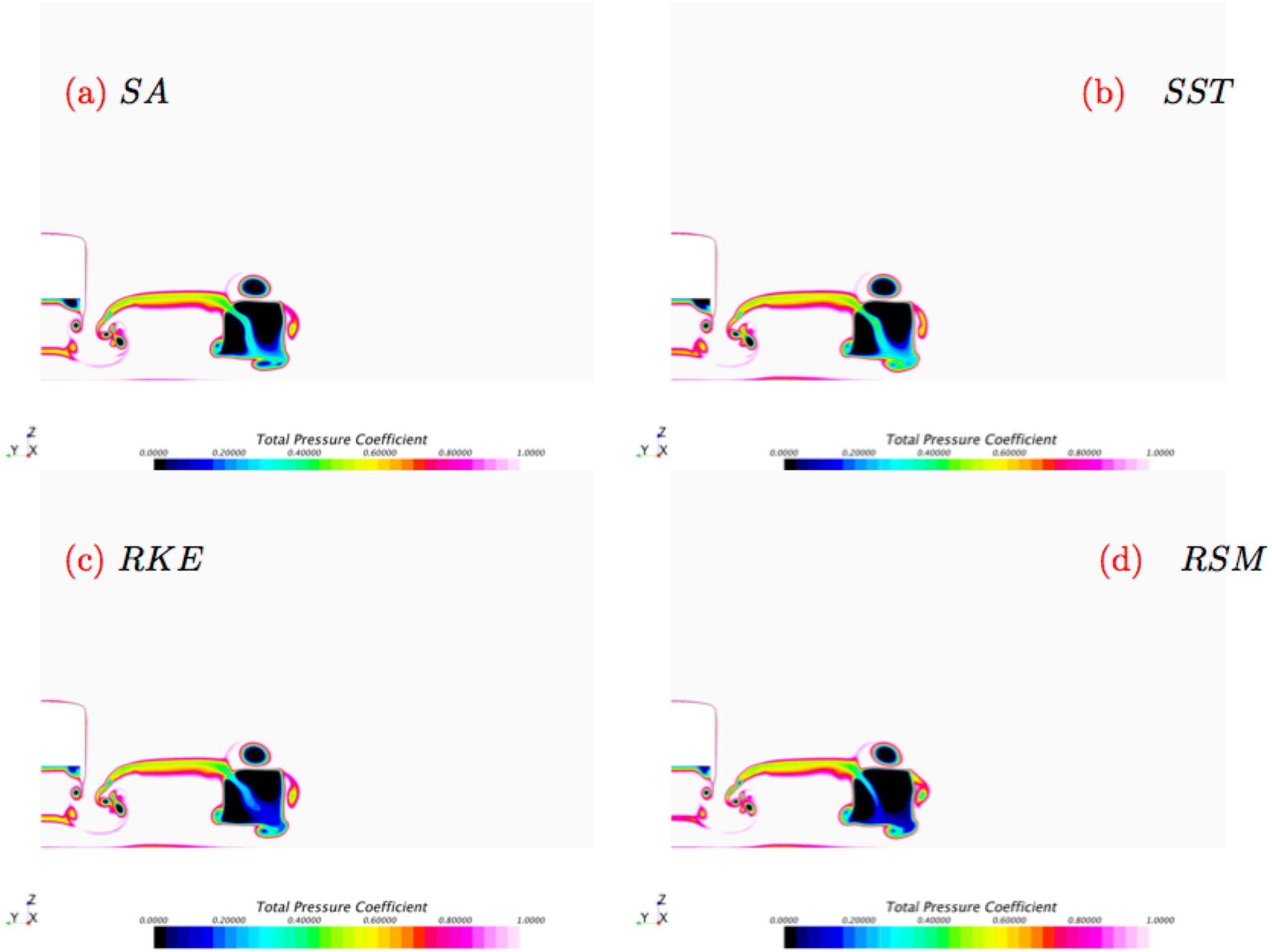
- SST under-predicts Cl due to greater sensitivity to separation
- Rotation+curvature sensing models predict greater Cl (towards exp. data) due to more persistant vortices

Model	Time per it.	Convergence (approx)
SA	14s	2000 it.
SA-RC	15s	2500 it.
RKE	12.5s	1200 it.
v2f	14s	1500 it.
SST	13s	4000 it.
EB-RSM	24s	8000 it.

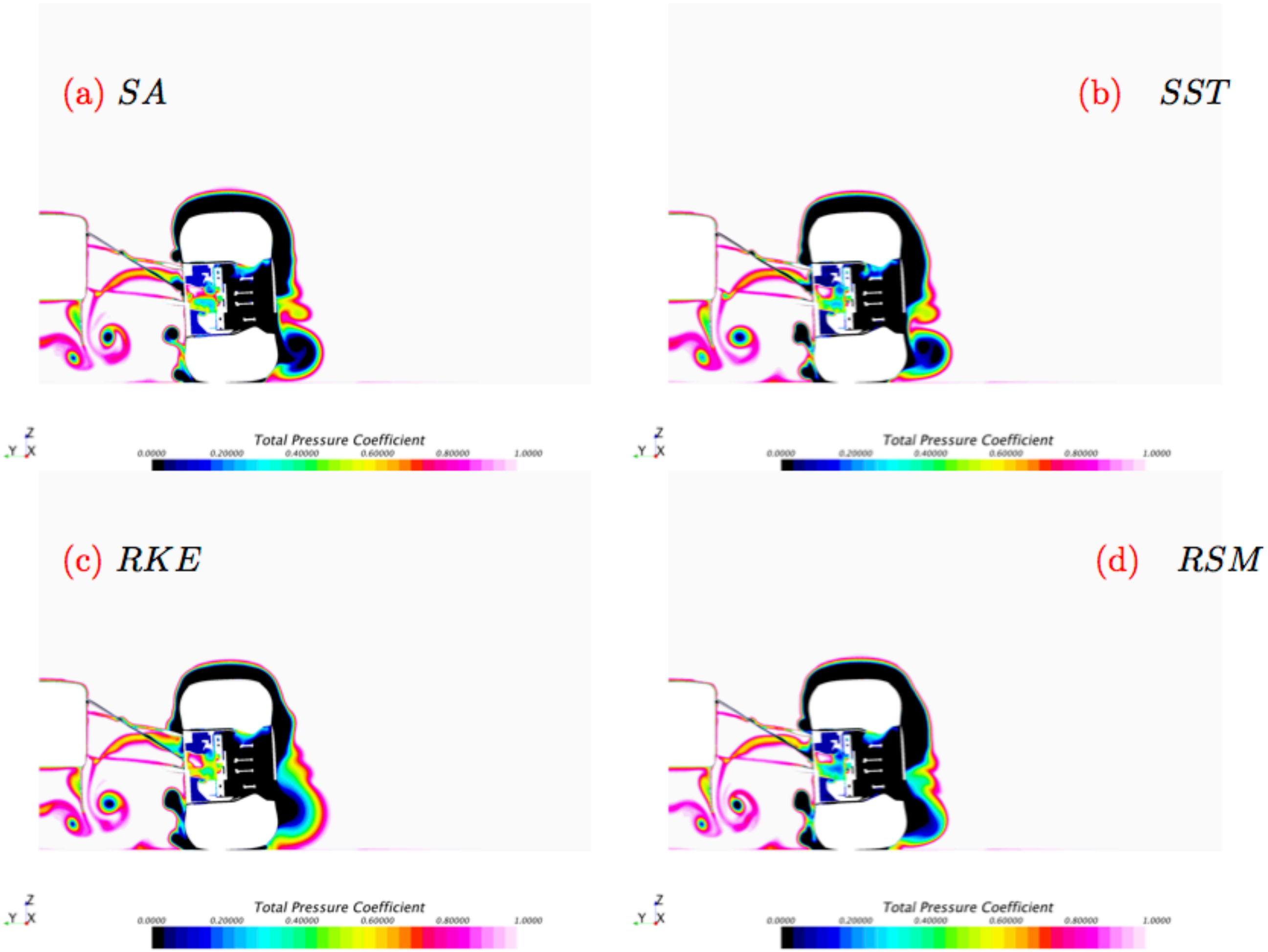
Turbulence Models



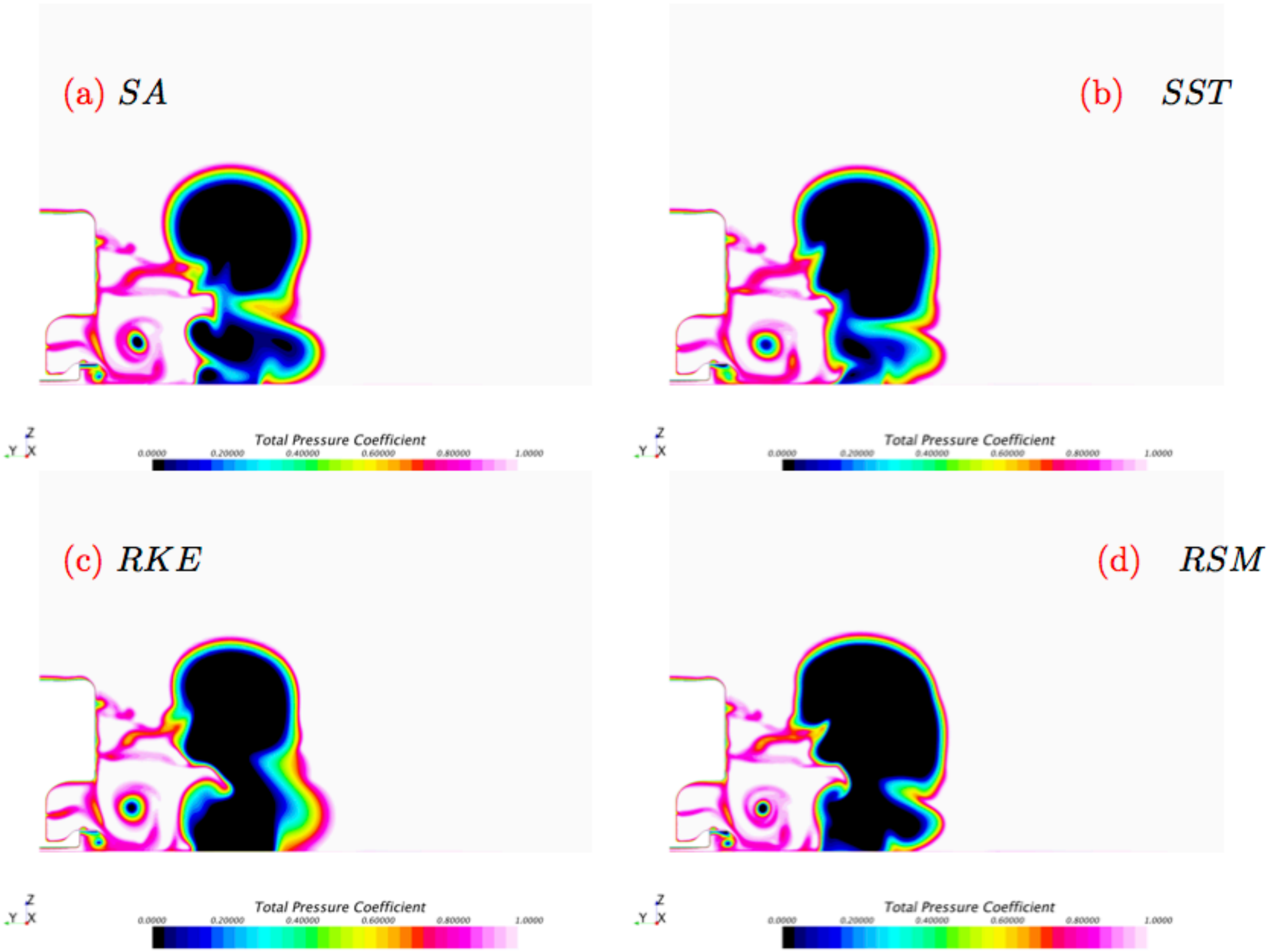
Turbulence Models



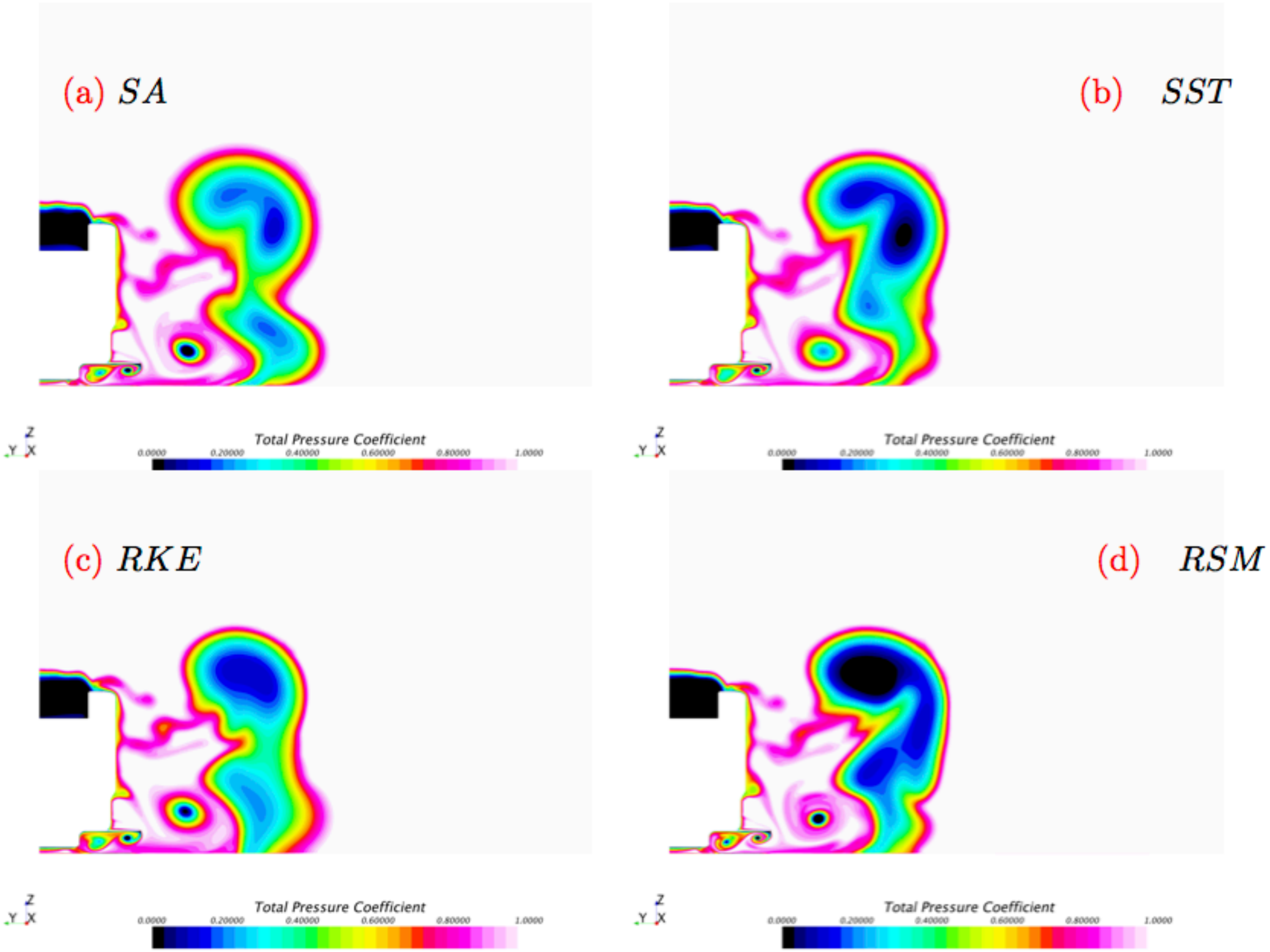
Turbulence Models



Turbulence Models



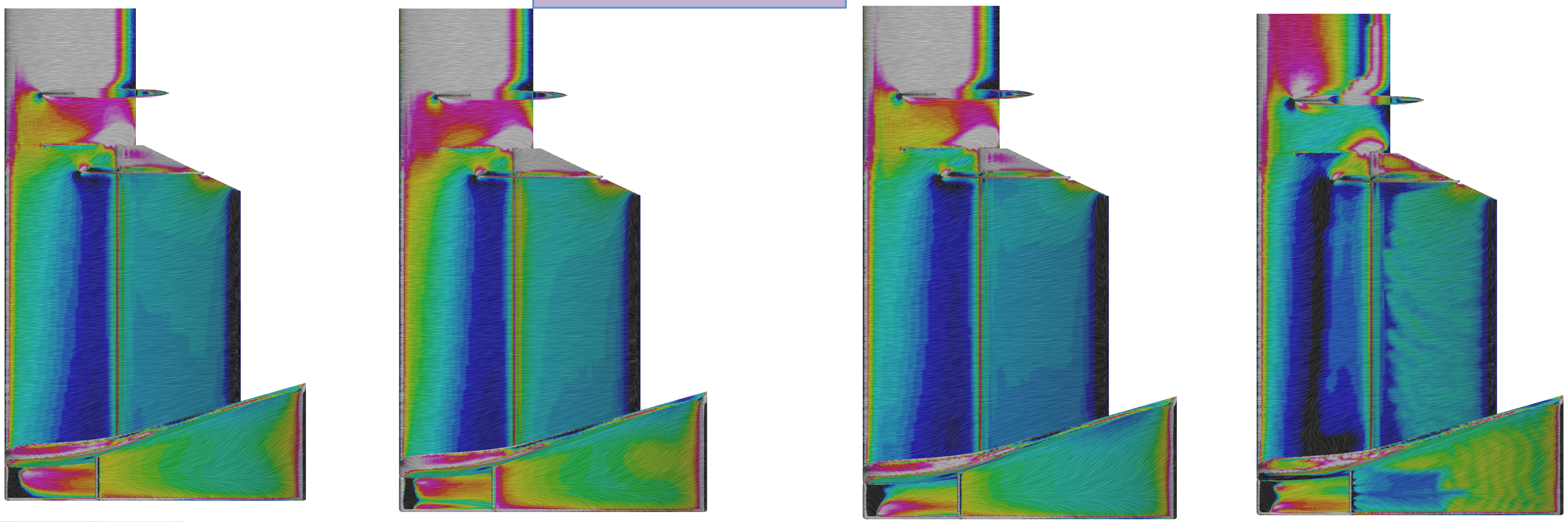
Turbulence Models



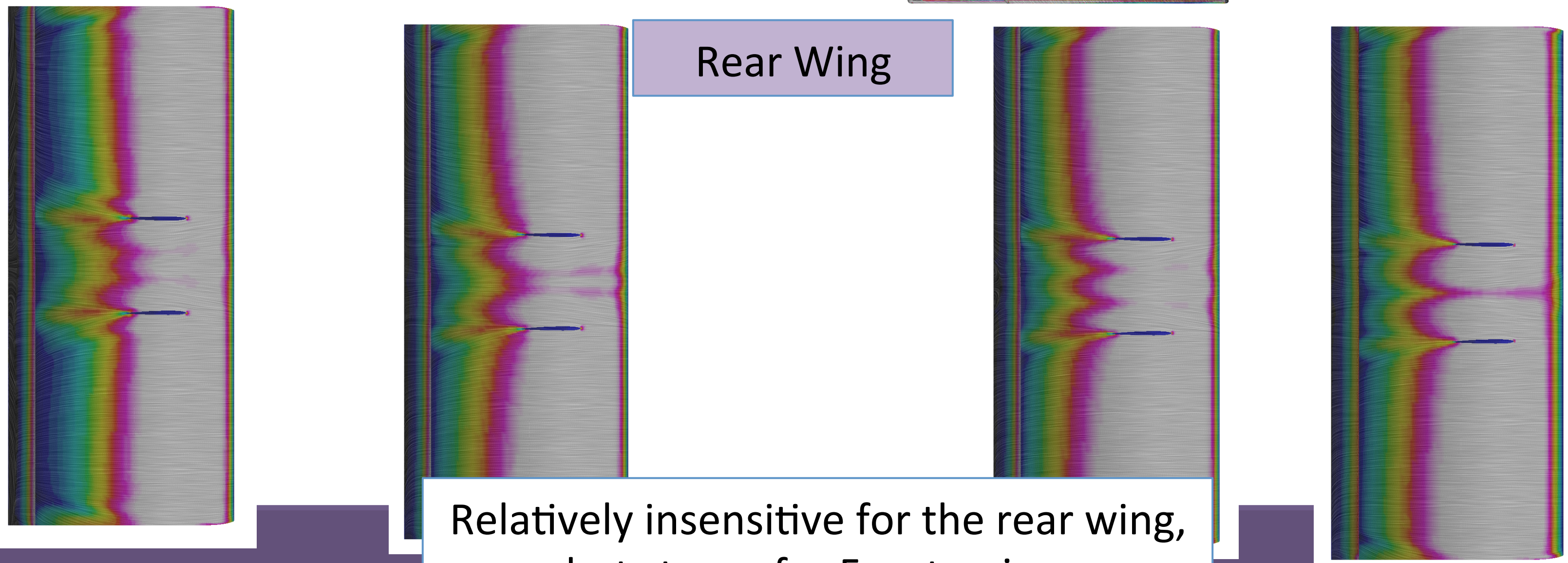
Turbulence Models

SA RKE SST RSM

Front Wing



Rear Wing



Relatively insensitive for the rear wing, but strong for Front wring.

Conclusions

- For Formula 1 (and many other industries) moving beyond steady RANS is too expensive for everyday design.
- Clear examples where RANS of all current state of the art models fail which makes the case for hybrid RANS-LES strong.
- More investment needed in developing improved RANS if moving to hybrid RANS-LES and beyond is not possible.
- Currently beginning work to develop a new RANS model suitable for automotive/aerospace flows. Identify flow physics where current models fail i.e initial separated shear layer (Work by Rumsey, Jakirlic have made progress in this area)

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Thank you